Investigation of Data Formats for the Integration of 3D Sensed and 3D CAD data for Improved Equipment Operation Safety

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Investigation of Data Formats for the Integration of 3D Sensed and 3D CAD data for Improved Equipment Operation Safety

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Abstract: Use of automation in construction is increasing at a rapid pace because it provides ways of dealing with skilled labour shortages, and of improving safety, quality and productivity. Much of this automation revolves around a control loop in which planned and designed assets are compared with what is currently in place. Comparing sensed and designed spatial data will be part of this broader process of comparison. This paper explores this issue by analyzing the characteristics of 3D sensed and CAD data, and investigating data formats that could be used for their integration. The focus is on the particular context of efficient 3D modeling for improved equipment operation safety. Results of an algorithm developed for converting 3D CAD data into point clouds are presented as a solution to one part of the challenge.

1. Introduction

A major need of the construction industry is to be able to compare construction to design. Such comparison can be used for construction deviation assessment, as-built recording, as well as construction automation. Automating such comparison may improve the speed and accuracy of these applications.

In order to efficiently compare 3D as-built to design data, it is typically necessary to first convert them into comparable formats. Generally, design data is obtained from CAD engines. As-built information is manually acquired during surveying operations, and the overall comparison of the two types is performed manually. This process requires significant time and expertise.

New technologies are being developed and are in use to ease and speed up such processes. In the case of construction as-built 3D deviation assessment, information can be obtained using LADARs, and then overlaid with 3D CAD information for manual comparison in an office setting (Cheok et al. 2000, Cheok and Stone 1999, Stone et al. 2004). This approach improves the efficiency (speed and quality) of this type of application. However, it is not appropriate for real-time applications such as equipment operation safety monitoring, and construction automation. Construction sites are dynamic and rapidly changing. Applications that must take into account this dynamic nature require specific data acquisition and processing techniques.

In this paper, 3D CAD and 3D sensed data are first described. Potential formats for integrating and comparing them are listed and analyzed with regards to their applicability for efficient 3D modeling for equipment operation safety. Next, some results of an algorithm for converting 3D CAD objects into point clouds are provided. Finally, conclusions are drawn and the objectives of future work are described.

2. 3D data

2.1. 3D Sensed Data

3D data are localization measurements in a 3D environment. In the construction industry, "3D sensed data" can be understood as 3D data of a physical infrastructure/building. In practice, 3D sensed data may be acquired to record 3D information of structural or architectural elements, as well as permanent or temporary elements. Consequently, 3D sensed data can be used in many different applications such as: methods identification, productivity and quantity tracking, deterioration assessment, quality/deviation assessment, equipment operation safety, and construction automation. Also, 3D sensed data can be acquired at any time during the life of the infrastructure/building starting at the construction stage. Acquisition of on-site 3D data can be done manually (most of the time today) or using some technologies allowing different levels of efficiency (time and quality) such as:

- Digital camera & stereovision (Jonker et al. 2000, Murray and Little 2000),
- Sonar (Dekneuvel and Medromi 1999),
- Laser-based scanners such as LADAR (Gordon and Akinci 2005), Range camera (Weingarten et al. 2004).

In all those approaches, the 3D data output has a point cloud format. "Dense" or "sparse" (Kim et al. 2004, Kwon et al. 2004), a point cloud is a list of 3D data points whose coordinates can be presented in Cartesian, spherical or cylindrical form.

2.2. 3D CAD Data

3D CAD data refers to the infrastructure/building design developed on a 3D CAD engine. In practice, 3D CAD data records 3D information of structural and architectural elements. Although temporary elements could be included in 3D CAD information, 3D CAD drawings generally only include information about permanent elements. 3D CAD information can be generated, consulted and reviewed at any time during the infrastructure/building life cycle starting at the design phase. As a consequence, 3D CAD information can be used for multiple applications during design, construction, maintenance, and decommissioning stages. There are many different CAD engines with many different data formats, and most of them are now developed for specific applications. Consequently, one of the major current AEC industry issues is the lack of CAD interoperability (Anumba 1996).

3. What format for what application?

In computerized CAD design, the type of project and the purpose of the drawings determine the most adapted data format. For instance, existing data formats for infrastructure/building structural and architectural design include DGN, DWG, DXF, IFC (Industry Foundation Classes). Also, earth surface modeling is commonly performed using DTM (Digital Terrain Modeling) formats like GIS (Geographic Information System). While these formats are developed for the purpose of designing new infrastructure assets or buildings with high levels of details, some applications may require different characteristics. For instance, a CAD drawing may very well need to be rapidly virtually traveled through with no need for all details. In this situation, the VRML (Virtual Reality Modeling Language) / XML format is, for instance, commonly used. Outside the construction industry, another interesting modeling format, the STL (Stereo-Lithography) format, is used for rapid prototyping applications for the manufacturing industry. This format, allowing rapid and fairly accurate 3D modeling, could be used for construction applications as further discussed later in this paper. On the contrary, sensed data formats are not numerous. The acquisition of 3D information generally produces 3D point clouds.

Some construction applications, including equipment operation safety, require or will require the full integration and comparison of 3D sensed and 3D CAD data. These applications can be gathered in two groups:

- Use of 3D sensed data for supporting CAD information.
- Use of 3D CAD data for supporting sensed information.

With regards to earlier discussion, data formats to be used in any of these applications certainly depend on the application itself. Furthermore, the point cloud format (3D sensed data format) is very different from most 3D CAD formats. The integration of 3D CAD and 3D sensed data is therefore not trivial (as illustrated in Figure 1). The following two sections examine in more detail the two groups of applications identified above.

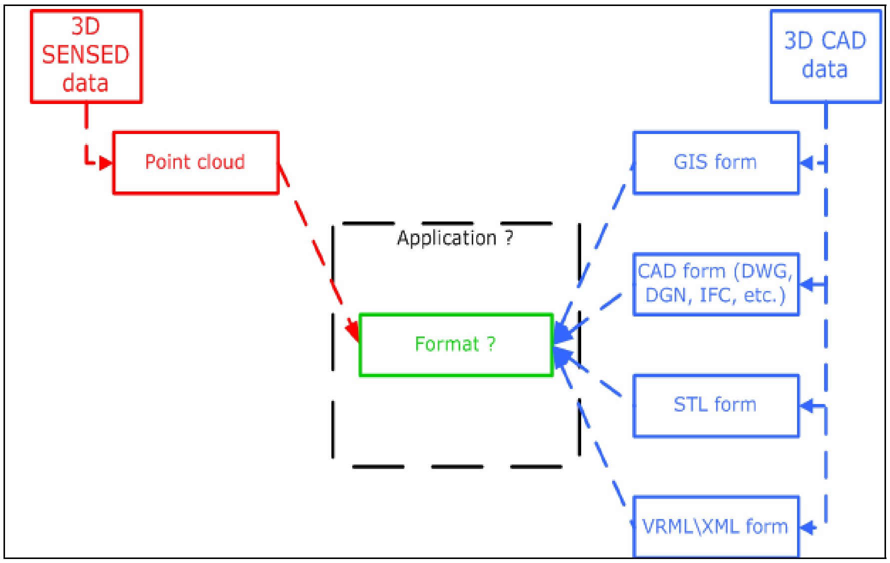

Figure 1. Integration of CAD and sensed data: what format for what application?

3.1. Applications where sensed data is used to enhance CAD data

Applications where sensed data is used for enhancing CAD data include construction progress assessment (as-built update), quality control, and infrastructure deterioration status assessment, and more generally "off-site" construction management support. Such activities require rapid but not necessarily real-time decisions. Therefore the frequency of information update does not have to be very high, which allows data acquisition and processing of higher quality. Such applications are already being investigated. LADAR/LIDAR –based approaches are for instance under intense development. Their concept is to import sensed information as dense point clouds into a CAD engine and fit standard CAD forms to manually or semi-automatically clustered point clouds. While the obtained results are very precise and accurate, many hours are generally required to acquire and specially process the millions of cloud points per scan. The next section will show that "on-site" applications require different, often opposite, characteristics that imply specific data acquisition, integration and processing approaches.

3.2. Applications where CAD data is used to enhance sensed data

Applications where CAD data is used for improving sensed information are those requiring rapid environment modeling and analysis, such as equipment operation safety, equipment path planning, and even construction automation. These can be viewed more generally as "on-site" applications. Their characteristics and data format requirements are discussed here in more details. Contrary to "off-site" processes, "on-site" construction processes must take into account the high rate of change of construction sites. The frequency of update of the information must thus be high, even real-time. This is achievable only as a trade-off resulting in lower accuracy and precision. The remaining of this paper details the data format investigation in the specific context of equipment operation safety.

4. 3D data formats for improved equipment operation safety

In the specific context of safety of operation of a piece of construction equipment, path interferences can be predicted and therefore avoided by dividing its 3D environment into “forbidden” and “allowed” zones. These zones do not have to be precisely defined but they may change dynamically (real-time change of position, orientation, and even shape). For instance, other pieces of equipment and workers may travel the operation space of equipment and thus constitute dynamic “forbidden” zones. In this application, the quality of 3D modeling is not as important as the frequency with which 3D models are updated. LADAR-based approaches are not appropriate and different sensing and modeling techniques must be used. This includes the identification of adequate data formats.

Previous research has been conducted on the use of 3D cameras for rapid environment modeling (Teizer et al. 2005). The research included the development of algorithms for: (1) importing point cloud into an occupancy grid, (2) filtering noise, and (3) clustering the data. The motivation to use an occupancy grid approach (Elfes 1989) is its robustness for fusing noisy data. Although the camera and image analysis algorithms have great potential for future application in the construction industry, the research results show some limitations. A major limitation is the sensitivity of real-time 3D modeling techniques to common effects such as shadowing. Clustering algorithms are used to detect and separate objects within the sensed data. However, since the laser technology used by 3D camera cannot get data behind objects, shadowing can significantly impact the clustering quality. Figure 2 illustrates the shadowing effect with the common situation where an object (e.g. a column or a worker) is between the sensor and a wall. Ultimately, this affects the quality of object detection, and higher level analysis such as object identification, interference avoidance and path planning.

A large part of the 3D objects encountered on a construction site are in fact parts of the project to be built, and are thus modeled in the 3D CAD drawings of the project. 3D CAD drawings could therefore be used as a source of a priori knowledge for refining and even correcting 3D models obtained from 3D sensed data. In the example in Figure 2, 3D data analysis techniques would typically detect three objects because of the shadowing effect of the front object over the wall. Besides, no additional information can be obtained from the sensed data that would suggest that the two back clusters must be connected to form a unique object. 3D CAD information about the back wall could be used for that purpose. The two back clusters could be recombined and the shadow space filled with the missing part of the wall. This ultimately improves the quality of the model and the higher level analysis based on that model.

Theoretically, this object inferred identification approach appears very interesting. In practice, this approach is challenging. As discussed earlier, 3D CAD and 3D sensed data essentially have different formats and are obtained from different sources. Data structures in which both data can be transformed and that would allow their real-time comparison must be identified. Besides, once the data is converted in comparable formats, algorithms must be developed for efficiently identifying CAD objects within the 3D sensed data.

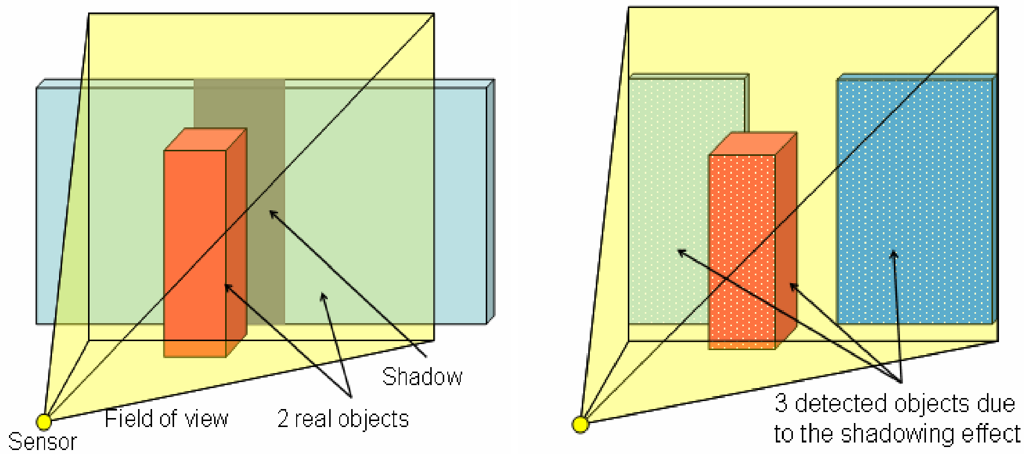

Figure 2. Example of the shadowing effect on 3D data clustering

4.1. Data Formats for rapid 3D modeling

For representing 3D environments in an accurate though real-time way, a few formats are already in use or under investigation for different applications throughout the construction industry as well as in other industries.

The most common format for rapid 3D modeling is the VRML (Virtual Reality Modeling Language) now being replaced by XML. VRML/XML is mainly developed for Internet applications. Large 3D CAD engine drawings can easily be transformed into VRML models. VRML models are much lighter than CAD ones, which allows rapid project fly-through without requiring enhanced computer capacities. This is achieved by removing all construction design characteristics from the drawing to keep only the visualisation ones. VRML models of 3D CAD drawings can be uploaded on websites and viewed by any allowed user from anywhere with a regular Internet connection and their quality is sufficient to be useful to the user. Besides, built-in VRML exporting functions are available on most CAD engines. Nonetheless, VRML has two major limitations. First, it is primitives-based which may limit the necessary modeling quality. Secondly, it is mainly developed for viewing purpose only, providing very little capacities for efficiently comparing 3D objects (e.g. interference detection).

A second format that has already been suggested for real-time construction 3D applications is convex-hulls (McLaughlin et al. 2004). A convex-hull, like a VRML object, connects vertices with lines to form a mesh or wire-frame. The resulting form is a series of polygons that represent its surface. Convex-hulls can be used to accurately represent the information contained in point clouds but with far less data. Convex hulls can be used in real-time processes such as real-time obstacle avoidance and path planning (Kim et al. 2004). However, the convex hull format presents one major limitation. First, convex-hulls, as their name indicates, are always convex. This means that any non-convex object (there are many non-convex objects on construction sites) can only be approximated by the closest bounding convex form, as illustrated in Figure 3 below. Ultimately, this can impact the efficiency of the comparison of the sensed and CAD data.

A third data format used for 3D modeling is the Stereo-Lithography (STL) format. The STL format, developed in the end of the 80’s by the Spanish company 3D systems, is very similar to the convex-hull and VRML ones in the sense that volumes are approximated by a wire-frame connecting vertices. Its purpose is originally to approximate complex volumes for rapid prototyping techniques that produce 3D volumes a layer at a time by using the light of a solid-state laser to trace the cross sectional slice information of the 3D CAD data onto the surface of a container of liquid photopolymer. The advantage of the STL format over the convex-hull format is that resulting volumes do not have to be convex. Convex-hulls are in fact a sub-set of STL forms. The advantage of the STL format is that most CAD engines have a STL-format exporting option, and sensed segmented point clouds can also be converted into convex-hulls. However, STL has a limitation which is that it is computationally complex to compute the similarity or closeness between STL forms.

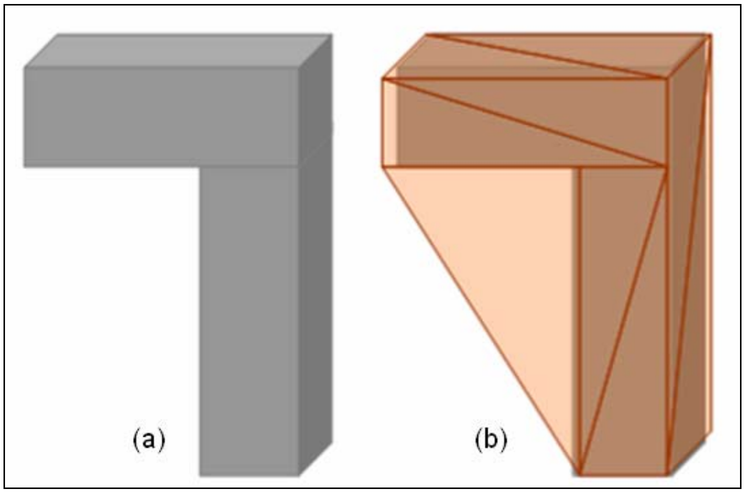

Figure 3. Illustration of the limitation of the use of convex-hulls for non-convex forms:
(a) Natural object form
(b) Most accurate Convex hull model of the object.

A fourth data format that can be used for 3D modeling is the point cloud format. The main advantage is that it is very simple to compare two point clouds – especially when imported in a common occupancy grid as implemented in the previous research presented earlier. The limitation, however, is that exporting a CAD object into an occupancy grid is not an exporting option built in a CAD engine and is a non trivial task.

4.2. Data Format Selection

First, the selection must take into consideration that 3D CAD information does not change with a frequency as high as the one with which the construction site state changes (~10^{-5}Hz vs. ~1Hz). As a result, efficient 3D modeling using 3D CAD data to enhance 3D sensed data must consider the least processing as possible of the sensed data. More time can be spent preparing 3D CAD data for efficient comparison with sensed data. This aspect suggests keeping the sensed data in the point cloud format (its natural format) and transforming CAD data into a comparable format. Other formats can also be used only if the sensed data can rapidly and accurately be converted into them.

Then, the selection must take into account the criteria for performing 3D data comparison in the context of equipment operation safety. The output of this comparison must be either "Yes, this sensed data cluster represents part of a CAD object" or "No, no sensed data cluster represents part of a CAD object". Besides, this comparison must be performed in real-time. 3D comparison criteria may include: center of gravity, flatness, and total volume. However, sensed data only contains information about the objects' visible surfaces (see Figure 4), while these criteria are only adequate for volume analysis and comparison. Another 3D data comparison approach is to quantify the closeness of the sensed data to the surface of the CAD object. For example, if 80% or more of the sensed data is less than 5 centimetres from the CAD object form, it can be deduced that the sensed data very likely corresponds to the CAD object's surface. In this approach, the sensed data can be used in its point cloud format and the CAD data in any format that represents its surface sufficiently accurately and that allows the easy calculation of the distance of the sensed data to the surface. Using the convex-hull format for the sensed data is not really suited for two reasons. First, it represents the sensed data as closed surface (volume). This representation is erroneous since the sensed data doesn't contain information about the hidden parts of the closed surface. The second limitation is that it is a complex task to compare the similarity or closeness between two STL convex-hulls - and more generally two STL forms.

As a result, it appears that, in the specific purpose of rapid 3D modeling for equipment operation safety, the sensed data should be used in its point cloud format (that can be imported in an occupancy grid). The CAD data could actually be used in different formats such as STL or point cloud. The following section presents some results obtained with an algorithm developed for converting 3D CAD data into point clouds.

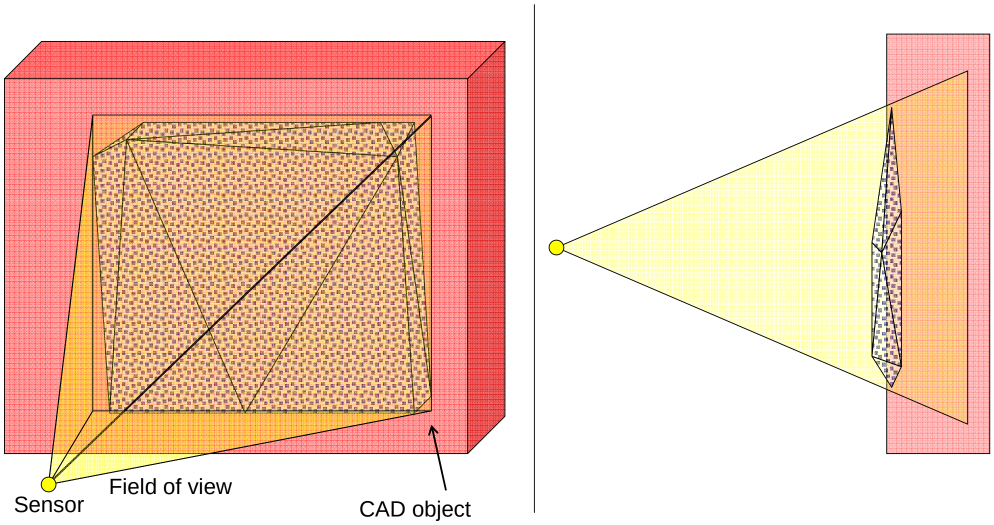

Figure 4. The limitations of the sensor 2 D field of view

5. Conversion of CAD objects into point clouds

While STL is a standard exporting format on most 3D CAD engines, no engine allows exporting 3D CAD objects into point clouds. Since the researchers are interested in assessing the comparison of 3D CAD and 3D sensed data using the point cloud format, an algorithm has been written to transform 3D CAD objects into point clouds. It is a two-step process: (1) Converting a 3D CAD drawing from the CAD engine into STL format, (2) converting the STL-formatted drawing into point cloud format. The resulting point cloud represents the surface of the object (not its volume). The resolution of the point cloud can be set by the user or, in the case where an occupancy grid is used, matched to the grid resolution. Figure 5 below shows an example of the two-step process with a simple canopy structure.

6. Conclusion

This paper identifies the need of the construction industry for real-time integration and comparison of in-site sensed and off-site CAD information. This would significantly impact the way projects could be conducted, with substantial time and cost benefits. One specific application is the assurance of the safe operation of equipment by modeling equipment environments in 3D for real-time interference detection and avoidance.

This task is complex due to the different formats that sensed and CAD data can have, the dynamic nature and randomness of construction environments, and the required real-time processing constraint. Furthermore, it has been demonstrated that data formats are closely related to the type of applications the data should be used for. Therefore, there are not one but many different formats that can be suggested for integrating sensed and CAD 3D data. In the specific context of real-time environment modeling for equipment operation safety monitoring, different existing formats could be used but the STL and point cloud formats were shown to be most appropriate. While CAD drawings can easily be exported into STL format, an algorithm has been specifically developed for converting 3D CAD drawings into surface point clouds. As a result, the real-time identification of 3D CAD objects within 3D sensed data can be performed using four different approaches (cloud-cloud, cloud-STL, STL-cloud and STL-STL). On-going and future work will focus on developing corresponding algorithms and comparing their efficiencies (speed and quality) against one another using experiments related to typical equipment operation situations.

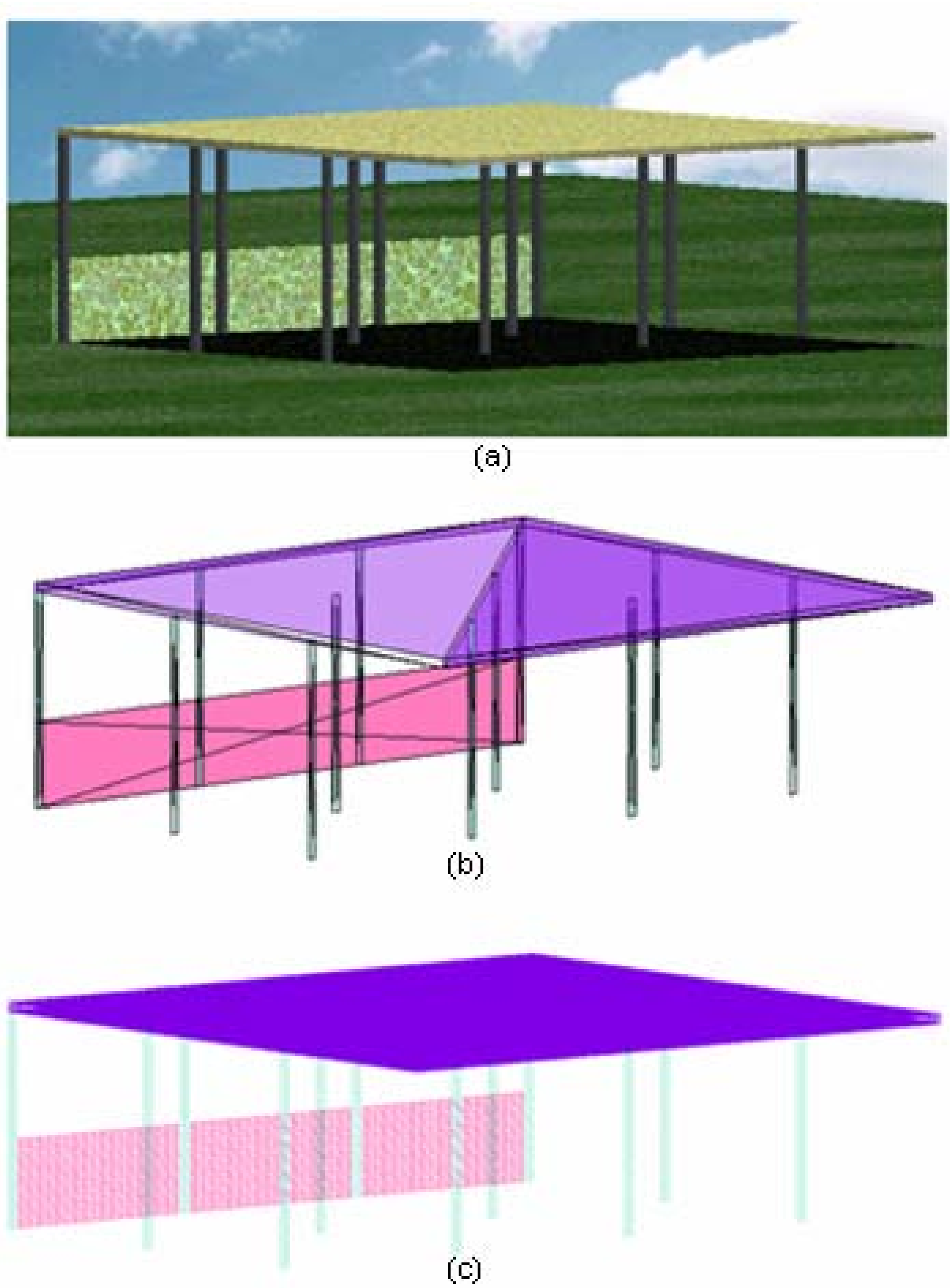

Figure 5. Example of transformation of a CAD object into a point cloud: (a) CAD rendering (Bentley Microstation) of a 15m x 15m canopy, (b) STL formatted canopy, (c) Surface point cloud of the canopy with a resolution of one point every 0.1m

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